Final report to the National Aeronautics and Space Administration Earth Science Enterprise

The Effects of Tropical Forest Conversion: Ecological Research in the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA)

From

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High Resolution Carbon Exchange over Large Scale Amazonia Based on Modeling & GOES Satellite-Derived Radiation Inputs

by

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A. Introduction

1.0 Mr. Andrew Grose successfully defended his dissertation this April (2004) and received the Ph. D. degree as a result of his LBA research, which forms the bulk of this report. His dissertation is entitled "**Variability Of Carbon Exchange Over Large-Scale Amazonia Based On Coupled Carbon Assimilation-Hydrometeorological Modeling And Satellite-Derived Radiation-Precipitation Inputs**".

2.0 A paper on the retrieval of down welling short wave and long wave radiation fluxes over the Amazon Basin from GOES Satellite resulting from this LBA research (Gu et al., 2004) has been accepted for publication in the Journal of Applied Meteorology this summer:

Gu, J., H. J. Cooper, A. Grose, G. Liu, M. J. Waterloo, A. D. Nobre, A. C de Araujo, A. O. Manzi, P. J. de Oliveira, C. von Randow, P. Slva Dias, J. Marengo, J. D. Merritt and E. A. Smith, 2004: **Variability of wet and dry season radiation fluxes and rainfall over Amazonia based on GOES retrieval.** Accepted for publication in *J. Appl. Meteor.*

3.0 Mr. Grose's dissertation is being partitioned into three papers (by myself and Dr. Eric Smith) that will be submitted for publication this summer, one involving the canopy, mixed layer and heat capacity modeling, another which will discuss the basin-wide results described in this report, and a third on the representativeness of a few strategically placed observation sites in the forest of the variability of CO_2 fluxes over the basin as a whole.

4.0 It was realized that for future research, the exchange of CO_2 between the vegetation and the atmosphere could only be properly modeled if the assimilation scheme was fully integrated into a mesoscale model, which would take care of the mixed layer and boundary layer interactions with the fluxes from and to the vegetation. To this end, the FSU hydrometeorological model has been fully coupled to a mesoscale model, the University of Wisconsin Numerical Modeling System (UWNMS), UWNMS has also been modified so as to advect changes in CO_2 concentrations originating in the vegetation at the surface into the mixed layer, the boundary layer and the free atmosphere above. Tropospheric CO_2 concentrations are now incorporated into the UWNMS long wave radiation code, which allows the effect of CO_2 variability in the horizontal and vertical on radiative cooling rates to be simulated in time and space.

B. Summary of Scientific Results

1.0 In Situ Analyses (Figures 1-5)

Result 1.1 Three different carbon assimilation models were examined for use in the FSU hydromet model. The NCAR LSM module was chosen because that model calculates respiration rates, and because the fluxes of CO_2, latent and sensible heat are also coupled through the stomatal resistance.

Result 1.2 Initial calculations of NEP and sensible heat fluxes using the NCAR LSM showed that **it was necessary to model canopy-boundary layer interactions and a canopy sensible heat capacity** in order to reproduce the observed magnitude and timing of persistent morning effluxes that are observed at Manaus and Jaru (Figures 1a, 1b).

Result 1.3 Morning sensible heat fluxes were consistently overestimated until canopy heat capacity was taken into account and **without it the sensible heat fluxes rose too rapidly in the morning** (Figure 1a), which affected the rise rate of the mixed layer, which in turn affected the CO_2 concentrations above the canopy, and hence the timing and magnitude of the morning effluxes from the canopy into the atmospheric surface layer (Figure 2).

Result 1.4 CO_2 concentrations in five layers in the canopy and in the surface and mixed layers above the canopy were therefore modeled with their associated fluxes. **A slab model of the mixed layer above the canopy was used to delineate the top model level** (Figure 3).

Result 1.5 Estimations of canopy heat storage were found using the difference between observed net incoming radiation and observed latent and sensible heat fluxes, defined as the observed total residual energy, **to estimate canopy heat absorption rates** (Figure 4).

Result 1.6 Calibration of model fluxes at the three tower sites was conducted using the modeled total residual energy at the forest sites and modified photosynthesis parameters at the pasture site.

Result 1.7 The combined canopy heat capacity and interaction with the mixed layer produced reasonable simulations of the mean diurnal cycles (Figure 5a) and mean weekly diurnal cycles (Figure 5b).

Result 1.8 Solar radiation and above-canopy air temperature were found to be the forcing parameters that **exerted the most influence** on modeled CO_2 fluxes at the tower sites (for example see Figures 7a and 7b).

2.0 Basin Wide Analyses (Figures 6-12)

Result 2.1 Eight months of hourly high resolution GOES satellite radiation data and 6-hourly interpolated ECMWF meteorological data **were used to force the model** over the entire basin (Figure 6).

Result 2.2 Application of the model over the Amazon basin showed that while vegetation type is an important background factor controlling CO_2 fluxes, **solar radiation was the primary cause of spatial and temporal variability** (Figures 7a, 7b).

Result 2.3 There is a diurnal cycle of large coherent areas of efflux of CO_2 over the forest that progresses from SE to NW in December, and from NE to SW in June (Figures 8a and b).

Result 2.4 Modeled CO_2 fluxes showed average forested area mean monthly uptake rates in the range of 1-3 μmol m^{-2} s^{-1} (see Table 1 and Figure 6)

	Overall				**Daytime**			
	Forest		***Pasture***		***Forest***		***Pasture***	
Month	**mean**	**σ**	**mean**	**σ**	**mean**	**σ**	**mean**	**σ**
Mar 1999	-2.82	11.14	-2.88	10.71	-5.04	10.84	-10.62	10.47
Apr 1999	-2.44	11.22	-2.18	10.06	-4.51	11.37	-9.33	10.10
Sep 1999	-2.13	10.85	-2.37	9.91	-3.83	11.06	-9.28	9.82
Oct 1999	-2.39	11.41	-3.41	12.09	-3.95	11.49	-11.52	12.51
Mar 2000	-1.71	8.28	-2.03	9.70	-3.61	11.25	-7.79	10.50
Jun 2000	-1.04	7.99	-2.23	9.88	-2.44	11.42	-9.48	10.37
Sep 2000	-1.36	8.80	-3.00	11.28	-3.00	12.24	-10.75	11.92
Dec 2000	-1.36	8.69	-2.75	11.43	-3.24	12.04	-9.91	12.63

Table 5: Monthly means and standard deviations (σ) for CO_2 fluxes produced by the FSU hydromet model for forest and pasture areas within the Amazon basin. Values for overall and daytime fluxes are in μmol m^{-2} s^{-1}, and negative means imply uptake by the vegetation.

Result 2.5 Comparison of GOES satellite and ECMWF-driven model fluxes with observations at the tower sites at Manaus, Jaru and FNS **showed the timing and phase of the satellite-derived fluxes to be correct** (Figures 9a, b and c).

Result 2.6 Comparison of satellite-driven model fluxes with observations at the tower sites showed that the use of ECMWF winds and temperatures as forcing produced larger morning efflux magnitudes than the observations suggest (Figures 9a, b and c). This was because the time interpolation of **the six-hourly ECMWF data generated spurious nocturnal stability** (Figure 10) that trapped the below-canopy CO_2 longer, **leading to** higher early morning concentration gradients between the canopy and immediately above the canopy, resulting in **larger morning effluxes** at the onset of morning turbulence. Notice that this is not a problem at the FNS pasture site, as expected. **The use of hourly**

ETA model output, for example, in place of the six-hourly interpolated ECMWF products **would eliminate this problem**.

Result 2.7 Comparison of CO_2 fluxes at nearly 20,000 forest points within Amazonia with overall forest mean values using eight months of model output (Figure 11) suggest that **flux observations from five strategically placed towers** used in conjunction with the existing towers at Manaus and Jaru **would be sufficient to reproduce representative area-wide CO_2 flux variability** (Figure 12).

C. Figures

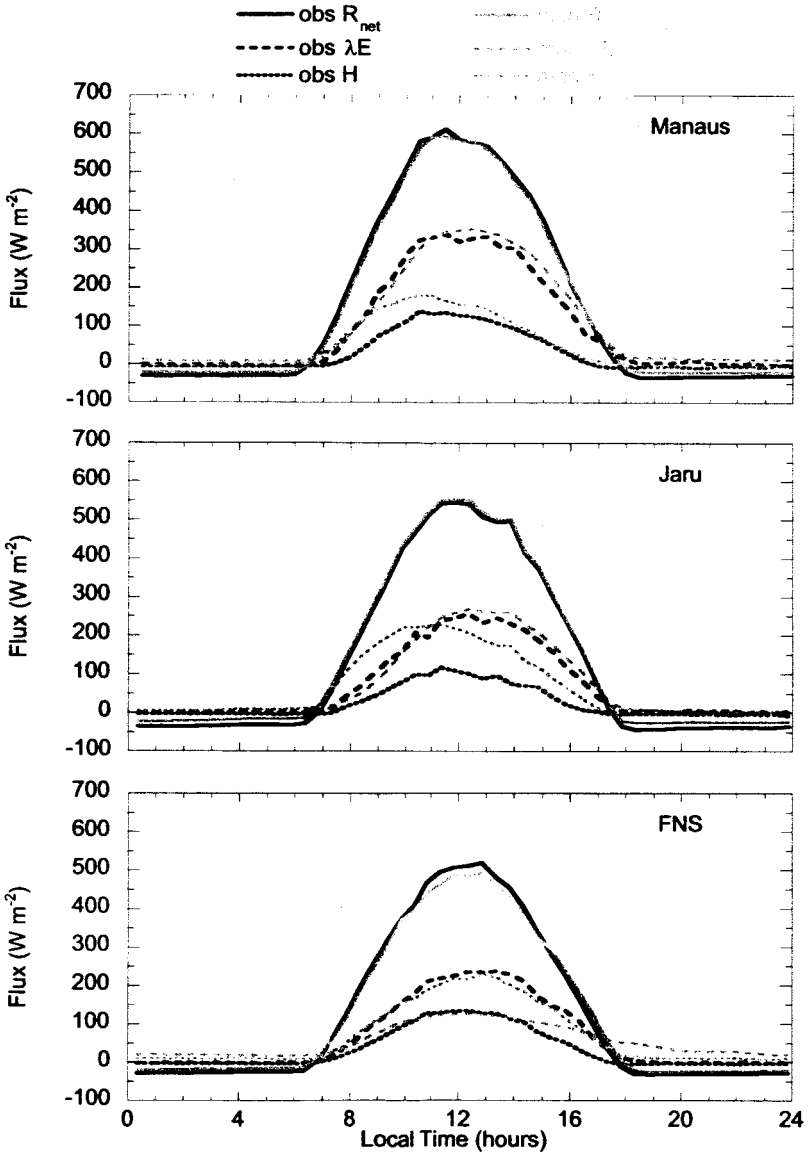

Figure 1a: Observed and modeled net radiation and latent and sensible heat fluxes **without boundary layer interaction and canopy heat capacity**. Note that only at the forest sites do the modeled sensible heat fluxes rise too early.

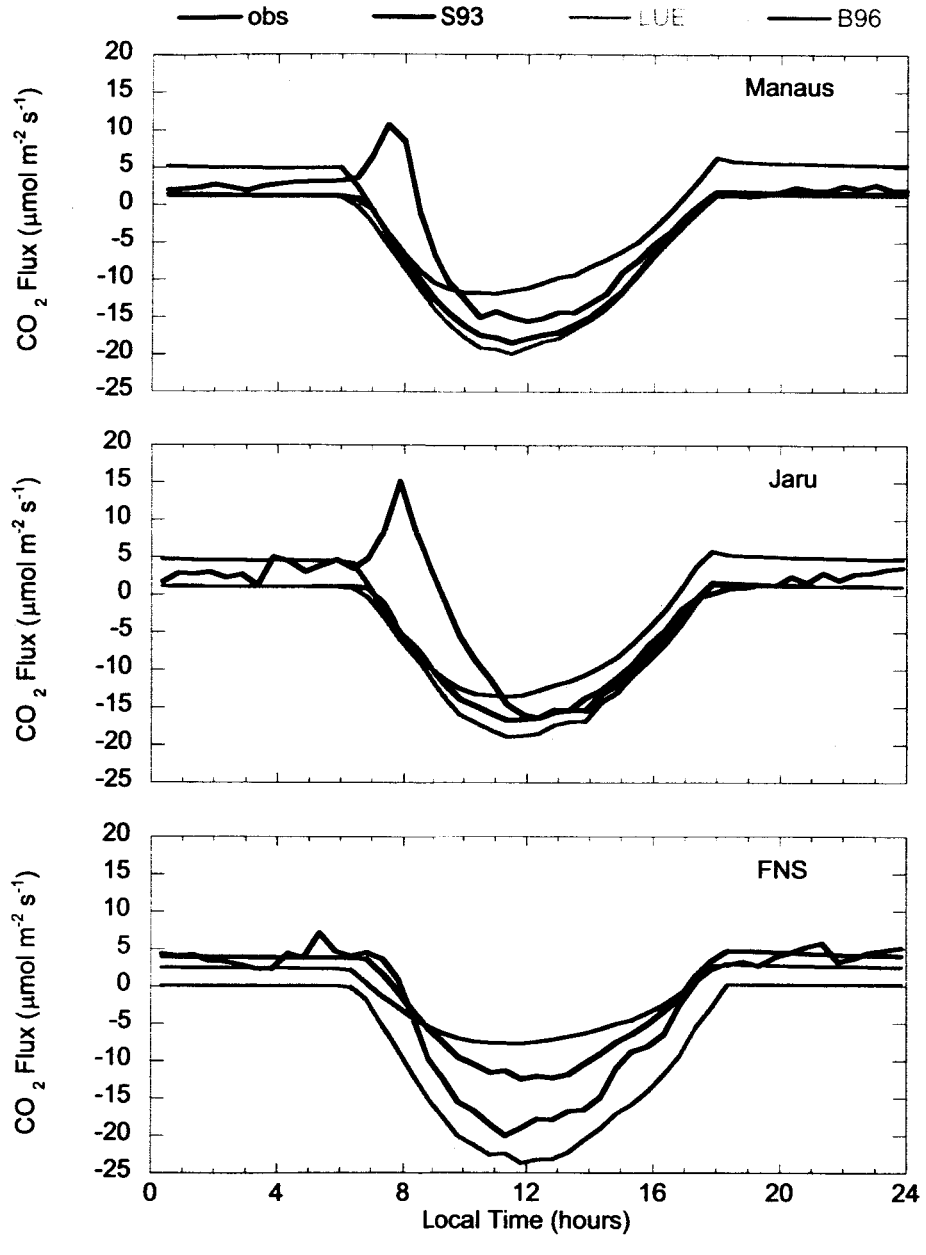

Figure 1b: CO_2 assimilation rates from three carbon assimilation models at the three tower sites compared to the observed CO_2 fluxes **without boundary layer interaction and canopy heat capacity**. B96 is the NCAR LSM, S93 is the model of Smith et al. 1993, and LUE is a light use efficiency model. The observations are in solid black.

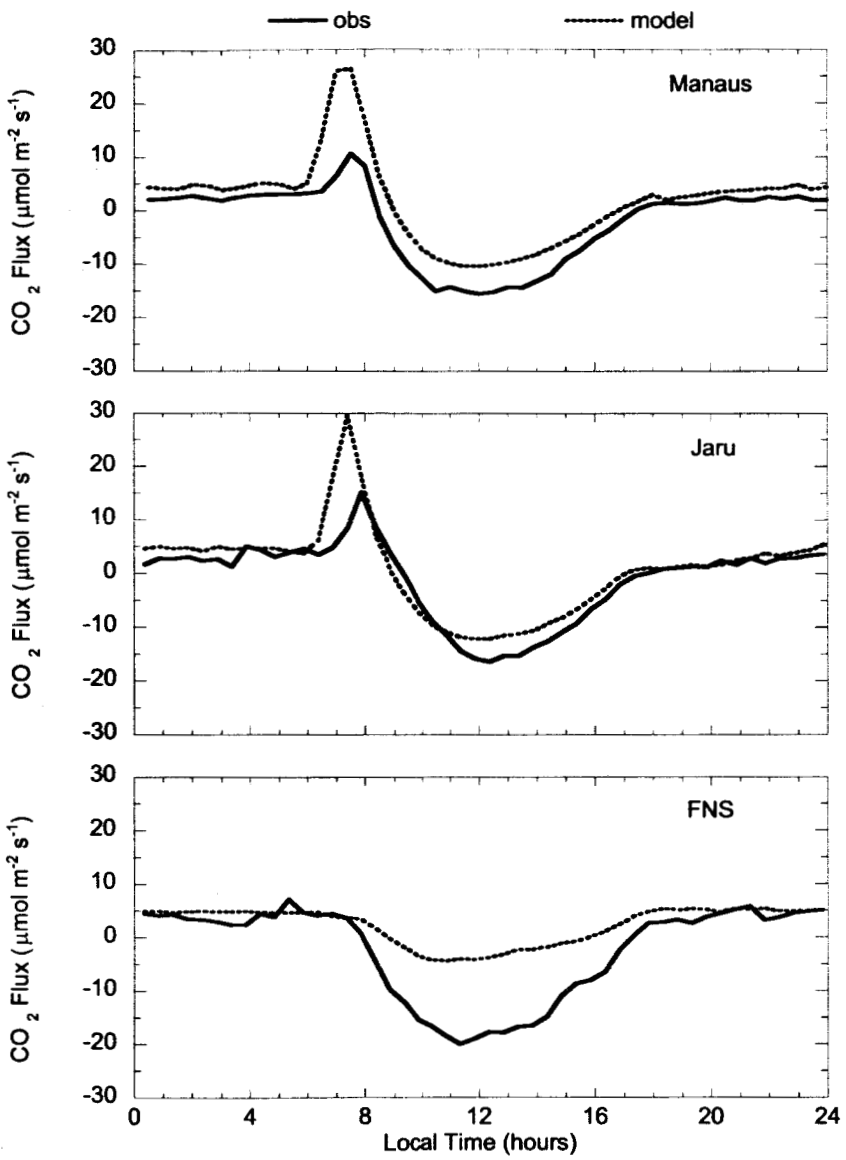

Figure 2: Mean observed and modeled CO_2 fluxes at the LBA tower sites **with boundary layer interaction but without canopy sensible heat capacity**. The morning effluxes at Manaus are too low, and those at Jaru occur too late. The large difference between the modeled and observed mean uptake at FNS was caused by the carboxylation parameters that were initially applied to the site, which were later found to be inappropriate.

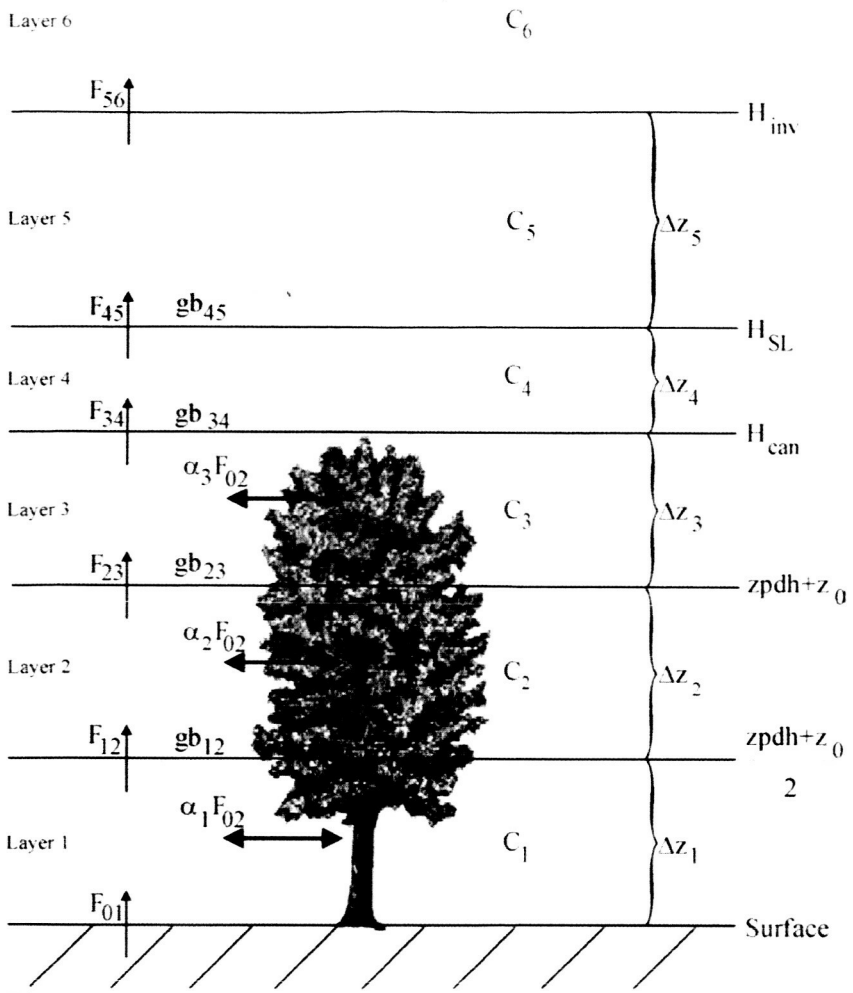

Figure 3: CO_2 flux model diagram. The boundary layer is divided into five layers; three in-canopy, and two above the canopy. Layer 6 is the free atmosphere layer above the inversion. *F* represents CO_2 fluxes between layers; *gb* represents conductances between layers; □*1*, □*2*, and □*3* are fractions of the canopy contained in layers 1, 2, and 3, respectively; *C* represents the CO_2 concentration in each layer; □*z* represents the thickness of each layer, H_{inv} is the height of the inversion; H_{SL} is the height of the surface layer; H_{can} is the height of the canopy; *zpdh* is the zero-plane displacement height; and z_0 is roughness height. Single digit subscripts represent values for a particular layer, while two-digit subscripts represent values at boundaries between adjacent layers. **H_{inv} is the height of the nocturnal boundary layer at night, and the height of the mixed layer during the daytime.**

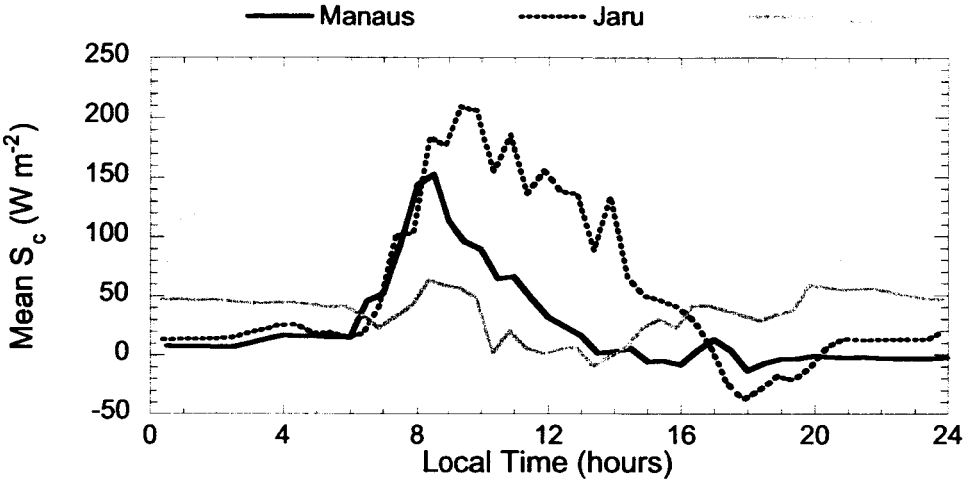

Figure 4: Mean modeled canopy storage (S_c) at the three tower sites using absorption rates calculated from the observed residual energy. Forest sites S_c values are the strongest in the morning and taper through the afternoon, while pasture site S_c values at FNS are generally higher at night and in the morning than during the day.

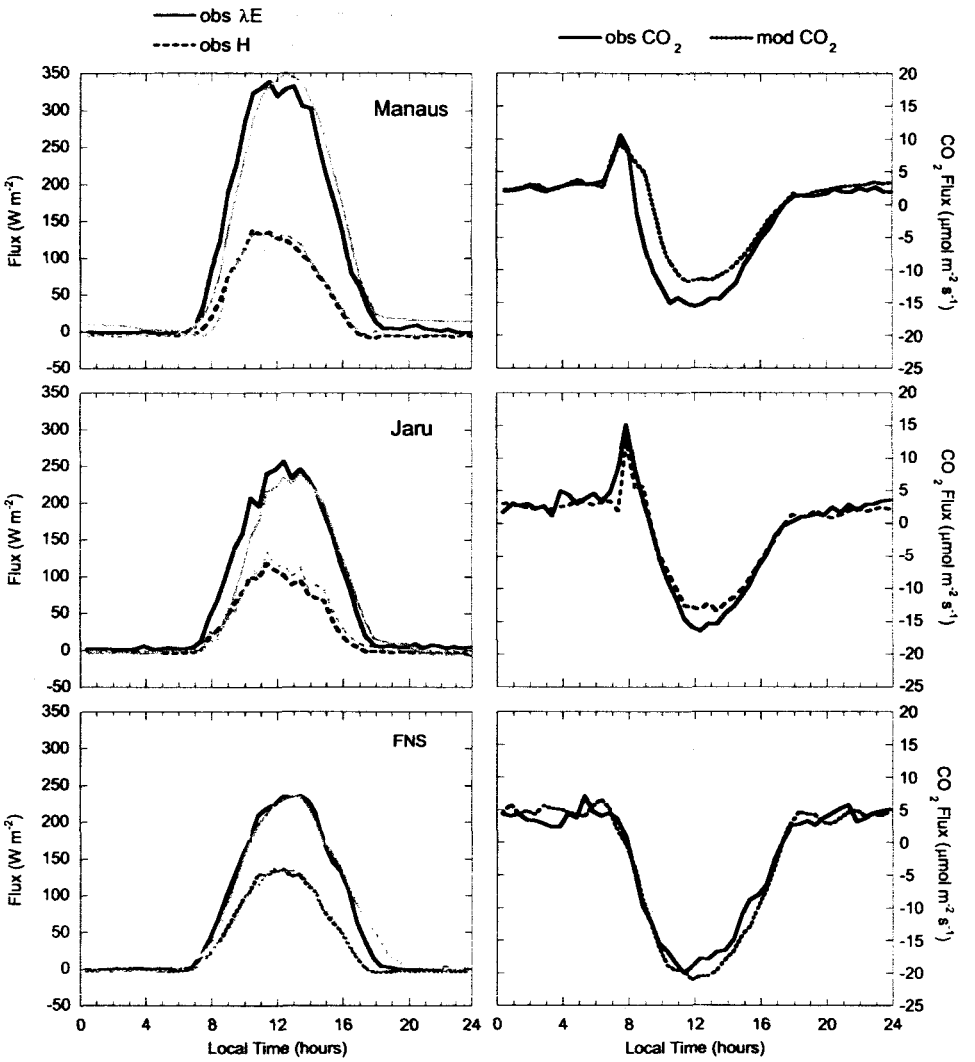

Figure 5a: Observed and modeled diurnal mean latent and sensible heat fluxes (left) and CO_2 fluxes (right) produced by the FSU hydromet model **including the mixed layer CO_2 flux model and canopy heat capacity**. Here the model is forced by observations at the tower site.

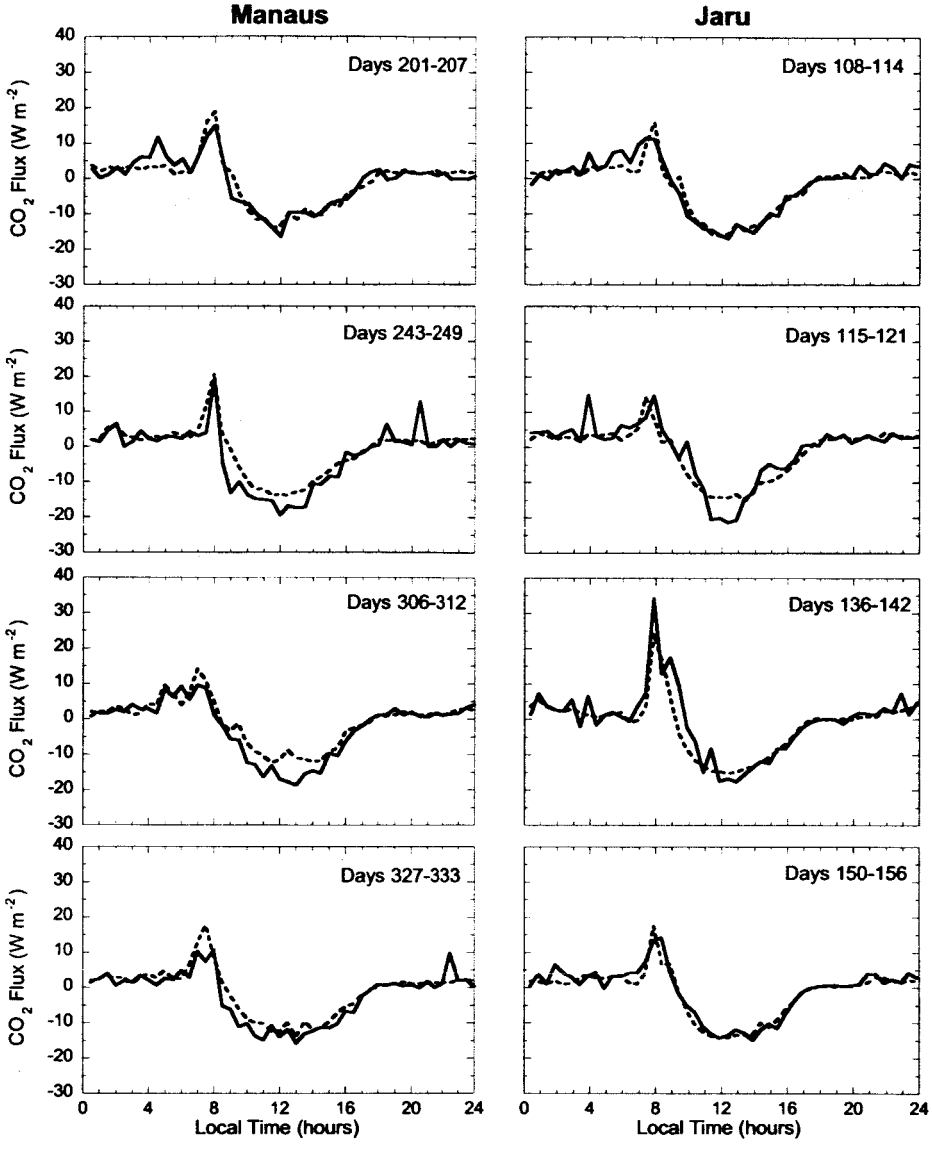

Figure 5b: Mean weekly observed and modeled CO_2 fluxes at Manaus and Jaru **including mixed layer and canopy heat capacity**. Solid lines represent observations and dashed lines represent modeled fluxes. Here the model is forced by observations at the tower site.

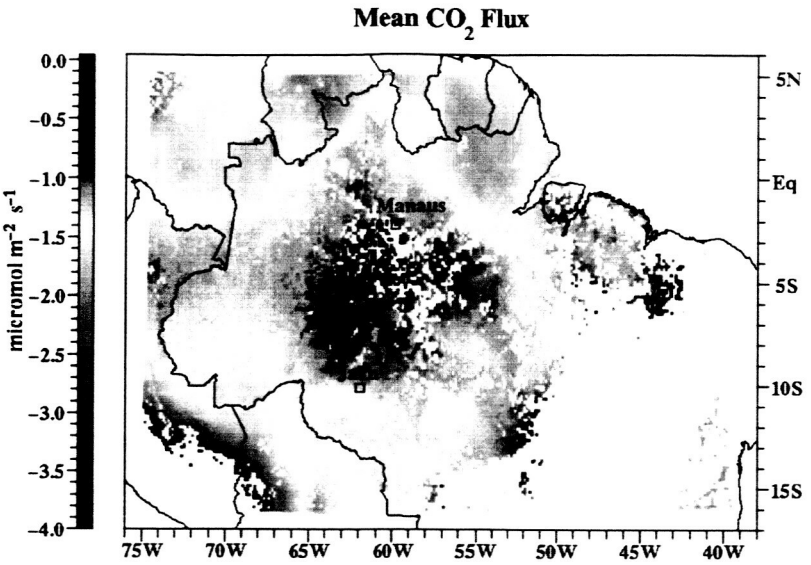

Figure 6: Mean modeled CO_2 flux over the tropical forest area in the Amazon basin. **Means were calculated at each point from eight months of hourly GOES-derived model output data**. Larger uptakes are in the higher elevation and cooler areas surrounding the basin. Blank areas have vegetation other than forest.

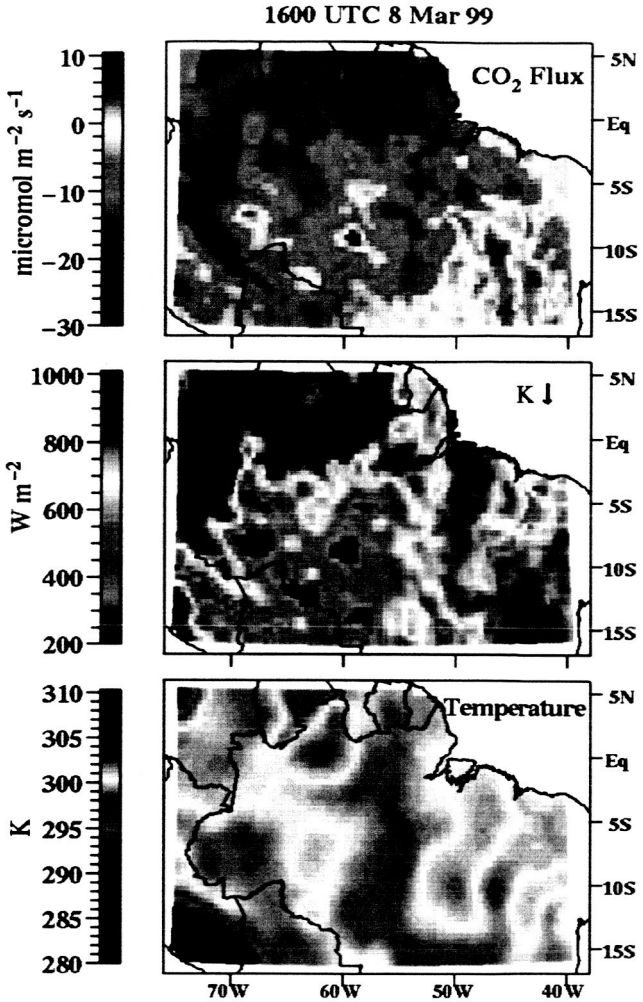

Figure 7a: An example of the effects of reduced solar fluxes (K↓) on CO_2 fluxes during the daytime on 8 March 1999. The central and southwestern regions experienced effluxes from the canopy rather than uptake during this time period due to significantly reduced K↓ from clouds and accompanying rain, which also reduced temperatures in the same areas.

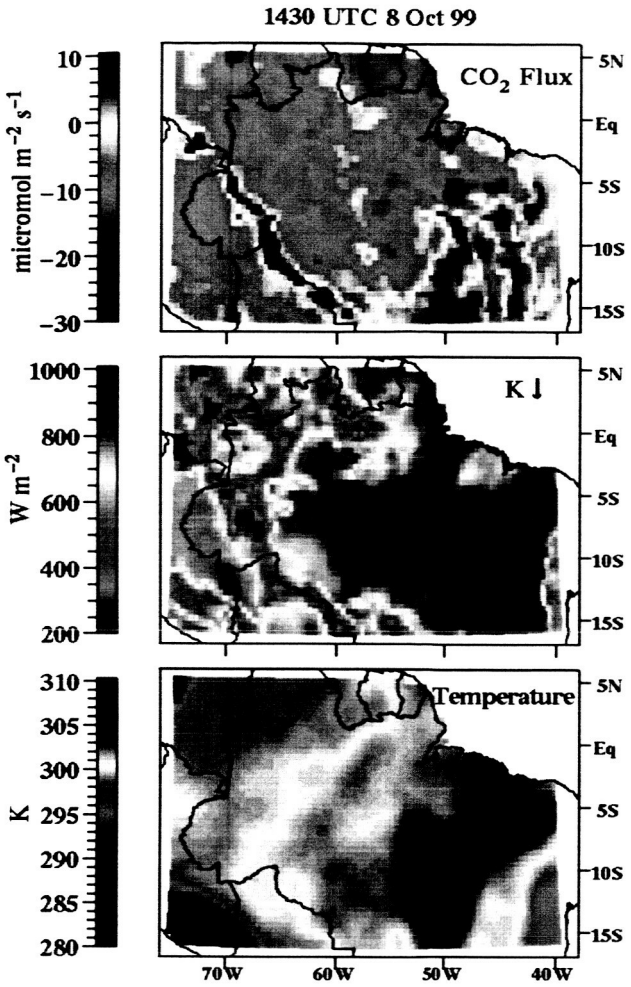

Figure 7b: As in Fig. 7a,but for 8 October 1999. A NW-SE oriented line of reduced K↓ is clearly visible in the western regions, which results in an efflux from the forest canopies along this line. Temperatures in the NW and SW are lower than temperatures in the central and eastern regions.

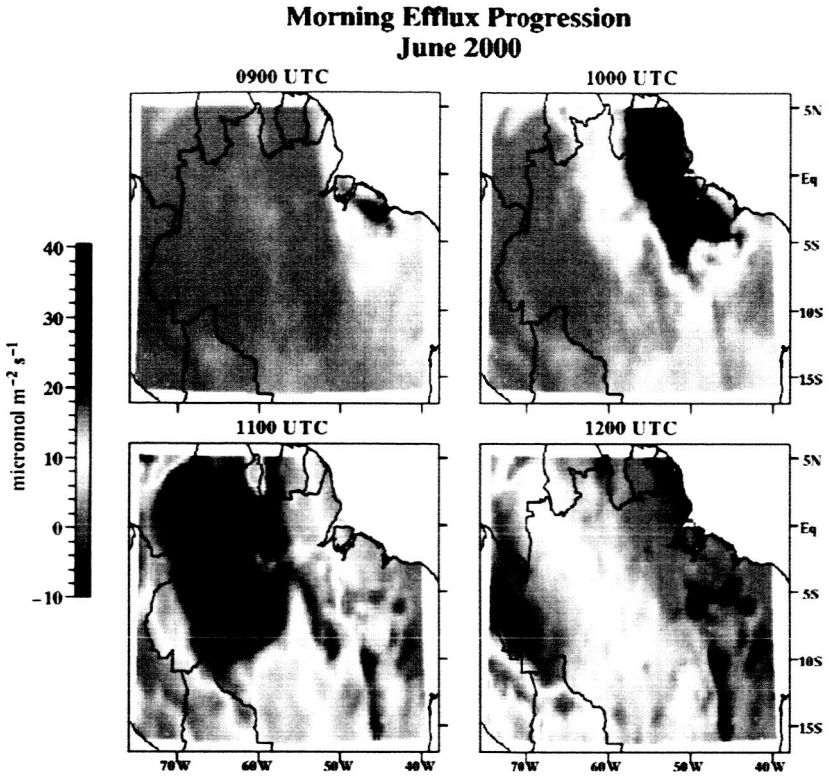

Figure 8a: Progression of mean modeled effluxes after sunrise in June 2000 from 0900 UTC to 1200 UTC. Sunrise in the region during June moves from the northeast to the southwest, and forest effluxes follow roughly the same path.

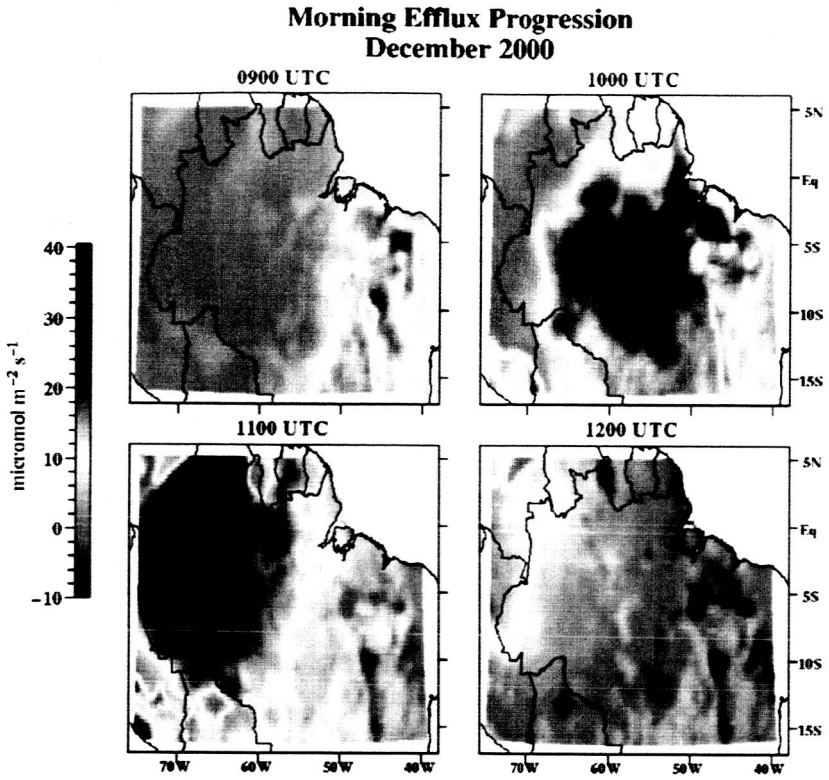

Figure 8b: As in Fig. 8a, but for December 2000. Sunrise in the region during December moves from the southeast to the northwest, and modeled effluxes follow a similar pattern

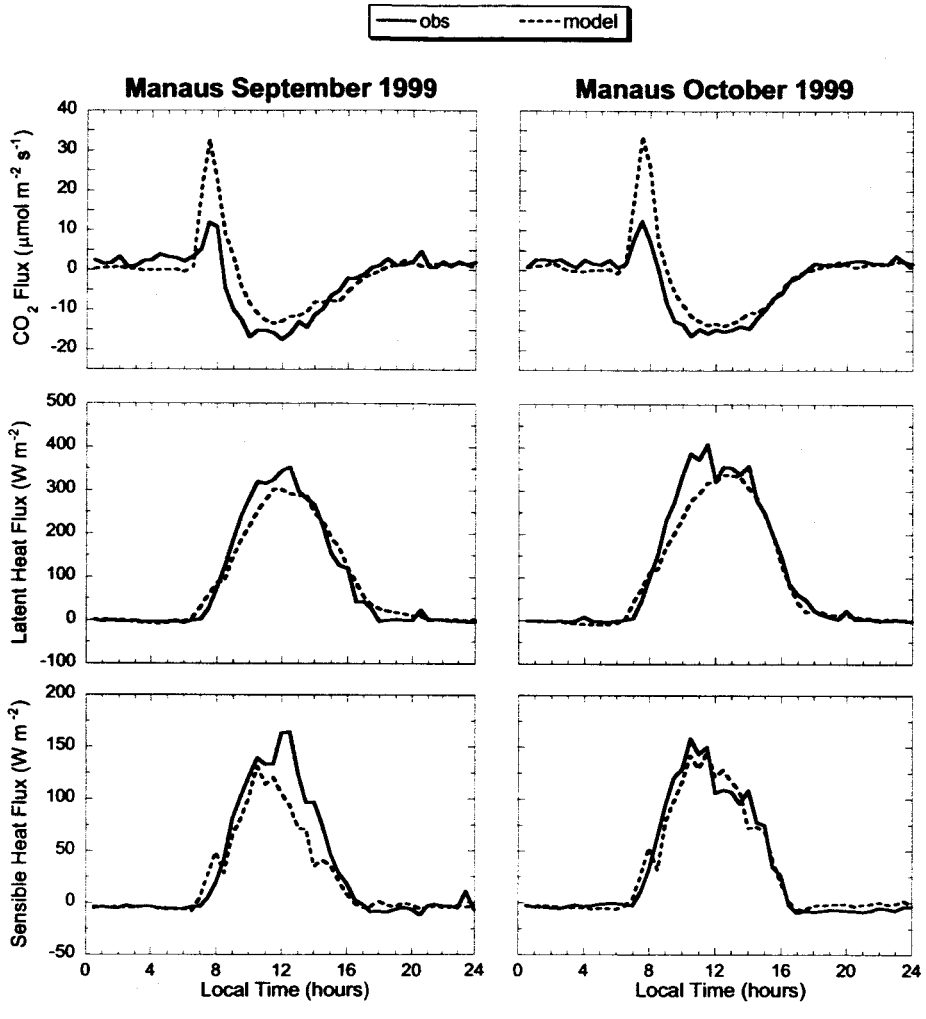

Figure 9b: Comparison of observed fluxes at the Jaru tower site with modeled fluxes **forced by GOES satellite and ECMWF data**. The excess efflux in the morning was caused by spurious stabilities introduced by interpolating the 6-hourly ECMWF above-canopy air temperature, a procedure that does not adequately capture the observed rise in morning temperature (see Figure 10).

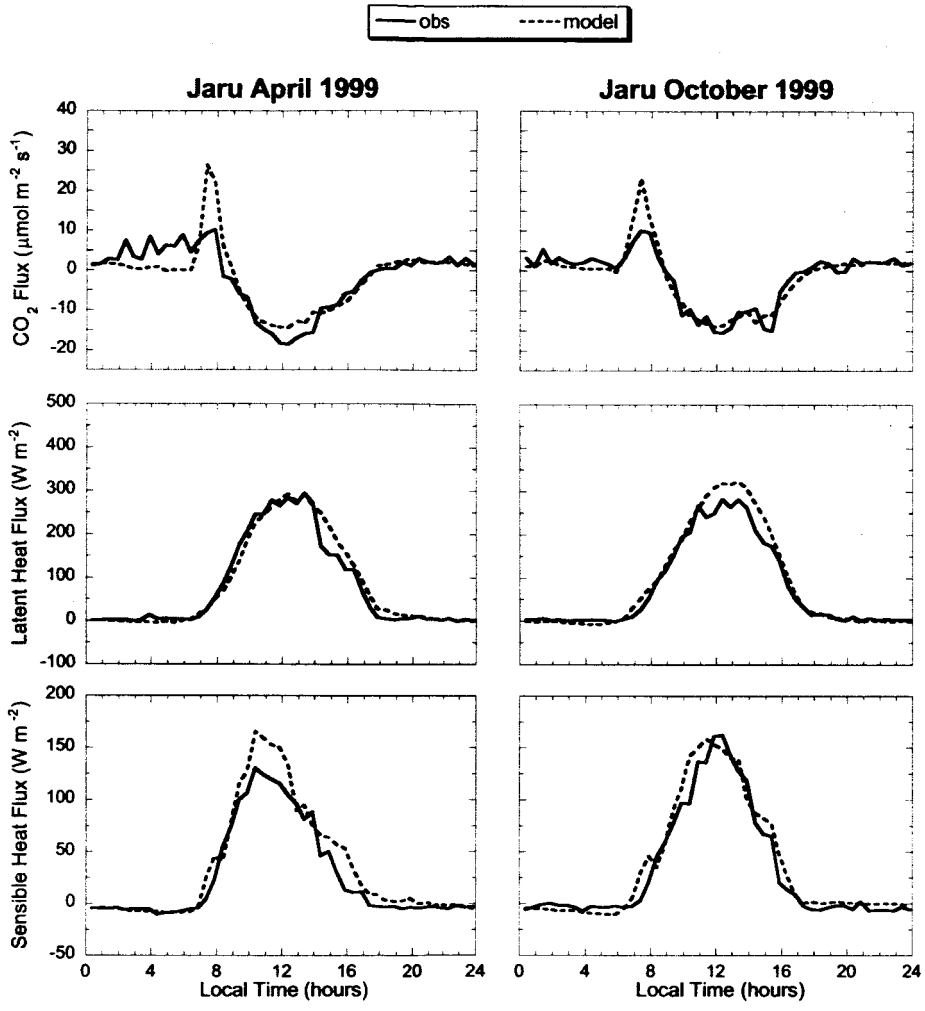

Figure 9b: Comparison of observed fluxes at the Jaru tower site with modeled fluxes **forced by GOES satellite and ECMWF data**. The excess efflux in the morning was caused by spurious stabilities introduced by interpolating the 6-hourly ECMWF above-canopy air temperature, a procedure that does not adequately capture the observed rise in morning temperature (see Figure 10).

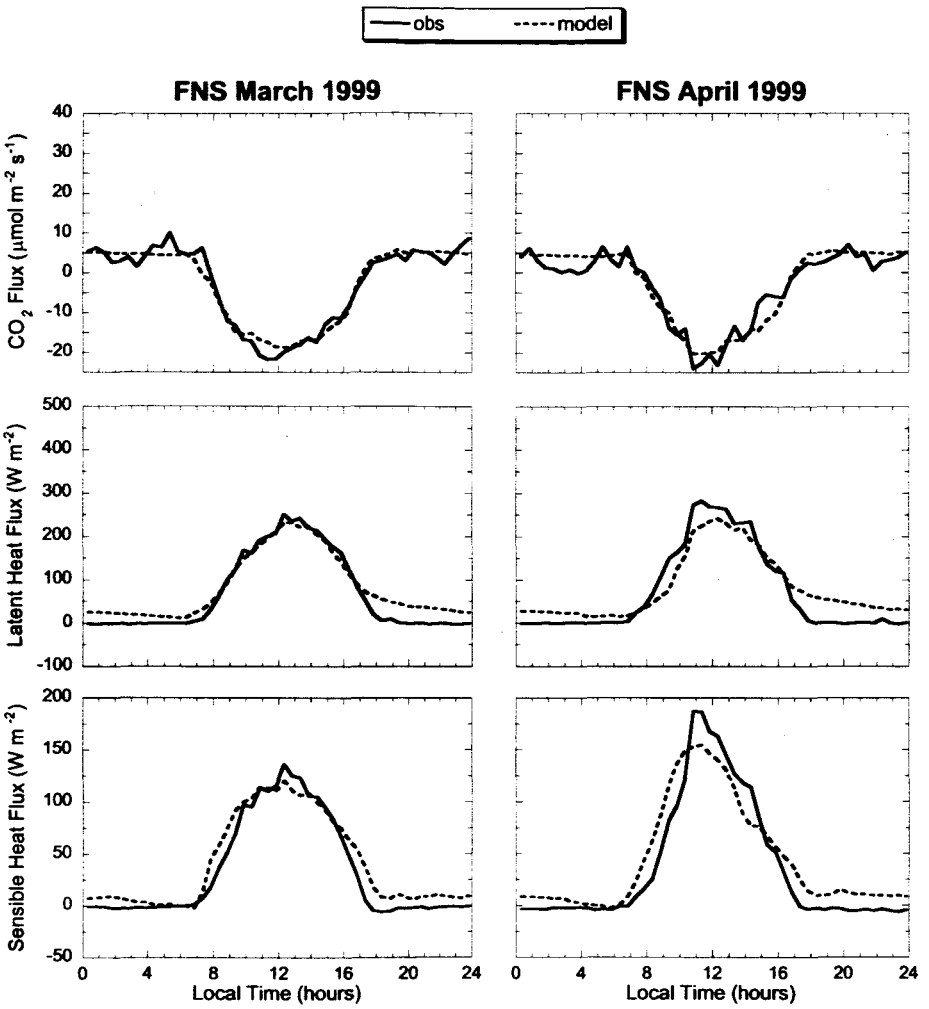

Figure 9c: Comparison of observed fluxes at the FNS tower site with modeled fluxes **forced by GOES satellite and ECMWF data**. Notice that spurious morning stability from ECMWF interpolation does not adversely effect the pasture calculations because CO_2 is not trapped to the same degree in the shallow pasture canopies as it is beneath the deep forest canopies.

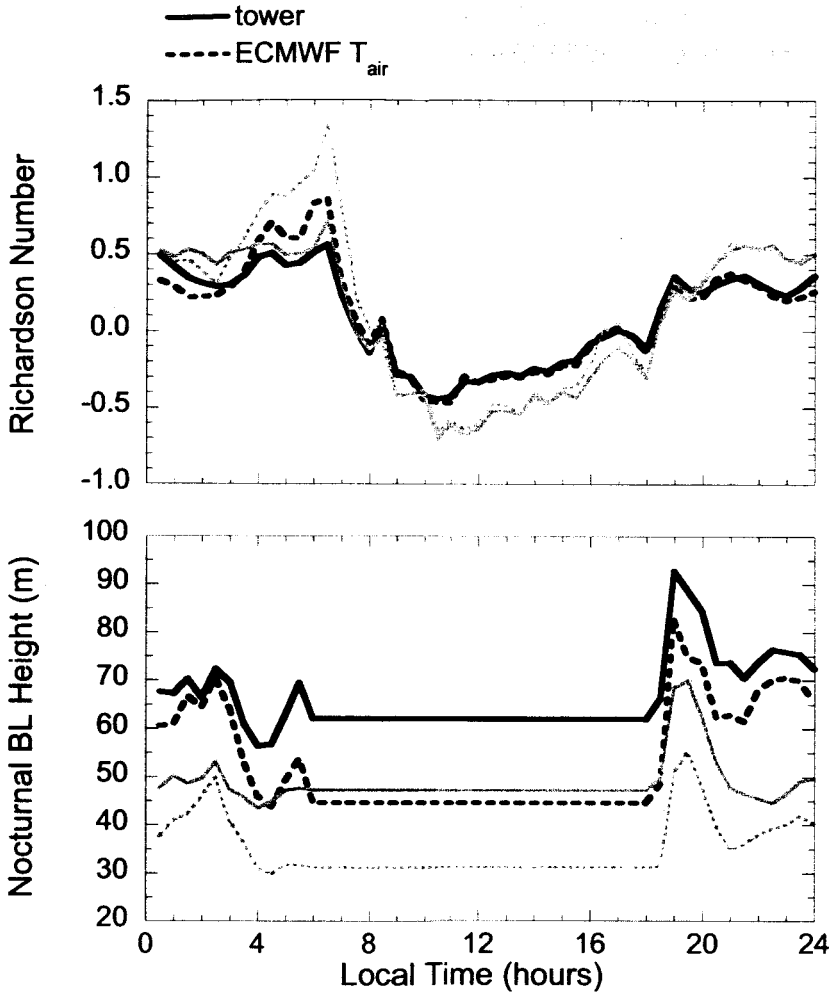

Figure 10: Comparison of modeled Richardson number and nocturnal boundary layer heights at Manaus during October 1999 using 1) only tower forcing data, 2) tower forcing data with T_{air} from ECMWF, 3) tower forcing data with winds from ECMWF, and 4) tower forcing data with both T_{air} and winds from ECMWF. Nocturnal boundary layer heights are held constant and are not used in the CO_2 flux model during the daytime when the mixed layer height is in use.

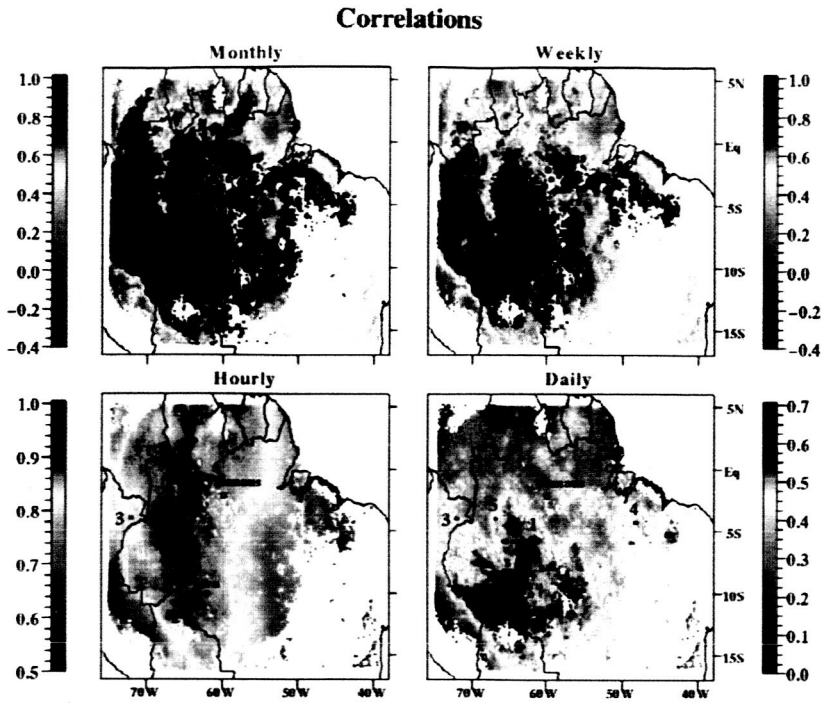

Figure 11: Correlations of forest points across the study area with the mean forest value for hourly, daily, weekly, and monthly time series using average forest values as truth. Numbers denote a rank of areas of high correlation for one or more of the four time scales. Area number 1 recorded the highest correlations across the range of time scales.

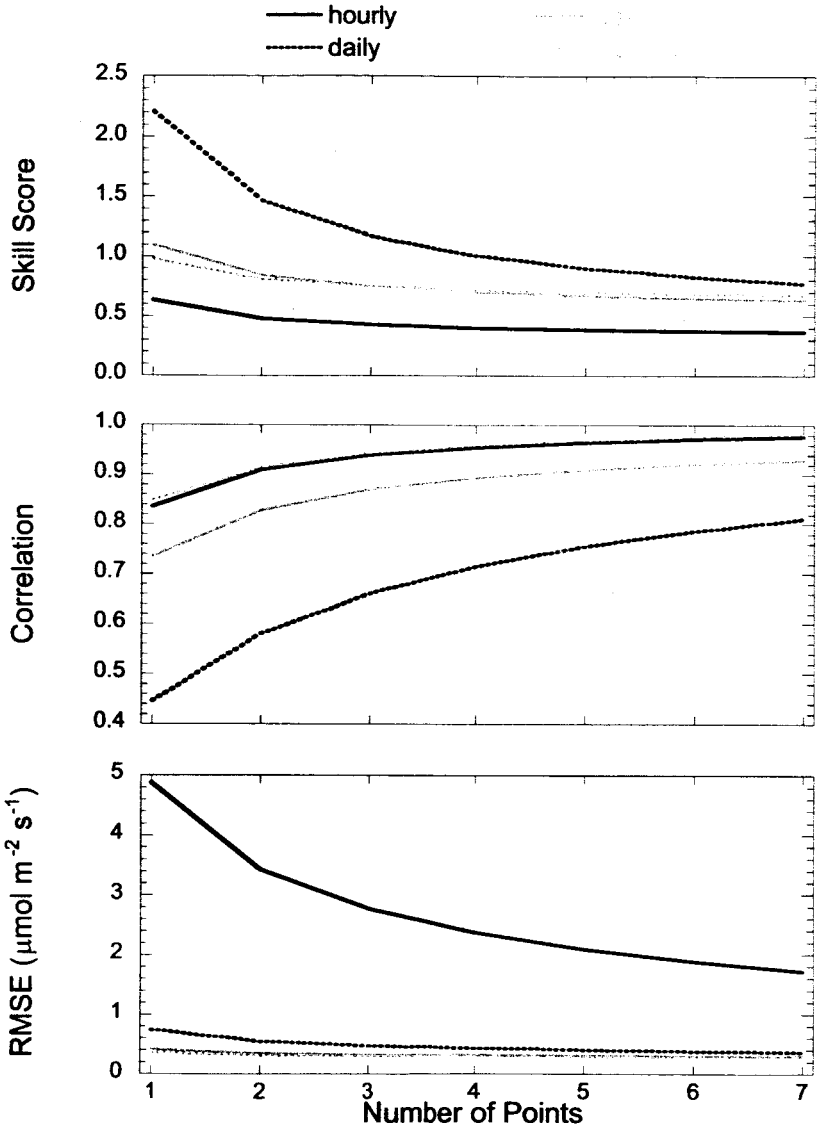

Figure 12: Average skill scores, correlations, and root-mean-square errors for CO_2 fluxes produced using combinations of the seven points shown in Fig. 32. Values are in comparison with mean forest CO_2 fluxes over the study area for four different time scales during the eight months of model output data.